Détection indirecte de Matière Noire : Les messagers neutres, gamma et neutrinos

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OHP, 10-16 Septembre 2007

Outline

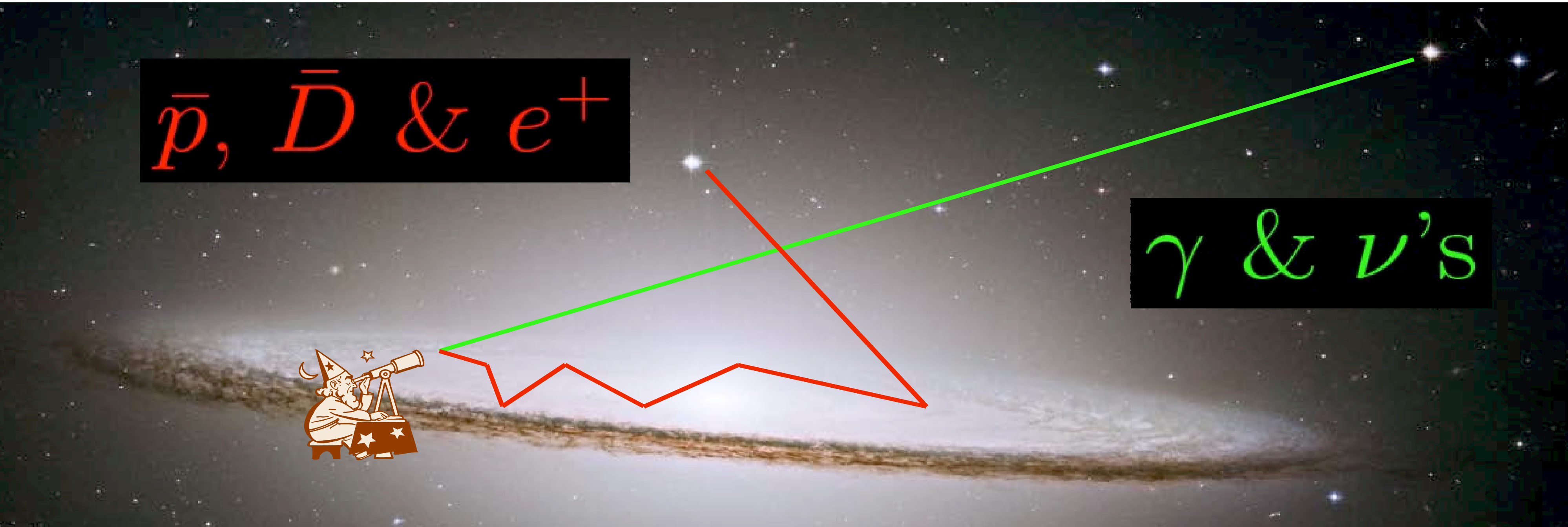
- **Gamma-rays: why, where and how**
  - Relevant parameters and degeneracies
  - Galaxy shapes
  - The spectral information and associated targets
  - Backgrounds
  - Clumpiness

- **Neutrinos: unambiguous messengers?**
  - Abandoning the galaxy-like targets ?
  - The Sun and the Earth: mechanisms and spectral properties
  - Other candidates: IMBHs

Running assumptions

- Dark matter annihilates ! (fairly motivated)
- Among possible encounters with candidates in this lecture
  - SUSY neutralino
  - Kaluza-Klein LSP in UED and warped ED theories
  - (Inert Higgs doublet, etc)

Gamma-rays versus antimatter cosmic rays



The annihilation signal is integrated:

- **over a small solid angle around the line of sight for $\gamma-$rays and neutrinos**
- **over a rather small volume around the Earth for antimatter CRs, due to diffusion processes**

$\Longrightarrow$ **Boost factors are not the same !**:

Astrophysical signatures: relevant quantities

In the very general case, flux predictions should read:

$$\frac{\mathbf{d}\phi_{\mathbf{CR}}}{\mathbf{dE}}(\mathbf{E},\tilde{\mathbf{r}}_{\odot}) \propto \frac{<\sigma_{\rm ann}\mathbf{v}>}{\mathbf{m}_{\chi}^{\mathbf{2}}}\int_{\mathbf{E}}^{\mathbf{m}_{\chi}}\mathbf{dE_S}\int_{\rm halo}\mathbf{d^3\tilde{x}}\mathcal{G}(\mathrm{E_s},\vec{\mathrm{x}}\rightarrow \mathrm{E},\vec{\mathrm{r}}_{\odot})\frac{dN_{CR}(E_S)}{dE_S}\rho^2(\vec{r})$$

........................which simplifies for gamma rays :

$$\frac{\mathbf{d\Phi_{\gamma}(E,\psi)}}{\mathbf{dE}} = \frac{<\sigma_{\rm ann}\mathbf{v}>}{\mathbf{8\pi m_{\chi}}^{\mathbf{2}}} \times \sum_{\mathbf{i}}\mathcal{B}_{\mathbf{i}}\frac{\mathbf{dN_{\gamma,i}(E)}}{\mathbf{dE}} \times \int_{\text{sight}}\rho^{\mathbf{2}}\left(\mathbf{s}(\psi)\right)\ \mathbf{ds}\ \mathbf{d\Omega}(\theta_{\rm res})$$

Particle Physics part :
$\rightarrow$ γ-spectrum, mass
annihilation cross section
Relic density constraint ?

Astrophysics part :
$\rightarrow$ density profile (theoretical/observational constraints from cosmology/rotation curves

The absolute flux: relevant parameter

A by-hand estimate of the γ-flux

$$\frac{\delta < \sigma v >}{8\pi}\left(\frac{\rho_\odot}{m_\chi}\right)^2 \approx 1.1\times 10^{-32}[\mathrm{cm}^{-3}\,\mathrm{s}^{-1}]\times$$

$$\left(\frac{\delta < \sigma v >}{3\times 10^{-26}\mathrm{cm}^3\,\mathrm{s}^{-1}}\right)\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\rho_\odot}{0.3\ \mathrm{GeV\ cm}^{-3}}\right)^2$$

$$.$$

$$N_\gamma(E_\gamma > 0.1\,\mathrm{GeV}) \approx 10 - 100\,/\mathrm{annihilation}$$

$$.$$

$$\mathrm{astro} \approx 4.9\times 10^{21}\,[\mathrm{cm}]\times$$

$$\left(\frac{0.3\,\mathrm{GeV\,cm}^{-3}}{\rho_\odot}\right)^2\left(\frac{M_\mathrm{gal}}{10^{12}\,M_\odot}\right)^2\left(\frac{10^2\,\mathrm{kpc}}{R_\mathrm{gal}}\right)^3\left(\frac{10^2\,\mathrm{kpc}}{D}\right)^2$$

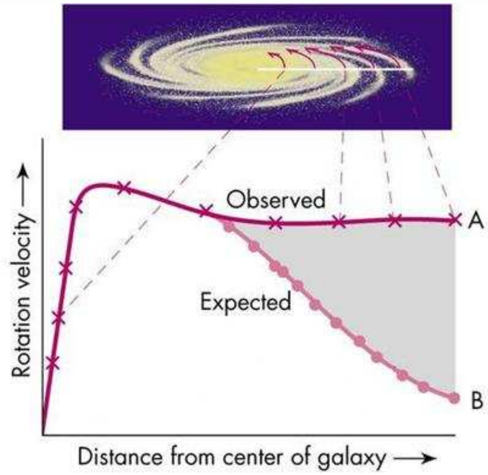
Estimate for the Milky-Way ($R\sim 8, D\sim 8$) kpc and M31 (100, 650) kpc

$$\phi_{MW}\sim 8.4\times 10^{-9}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\quad \phi_{M31}\sim 1.3\times 10^{-12}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Dark matter profiles in galaxies

Constrain the dark matter distribution in galaxies

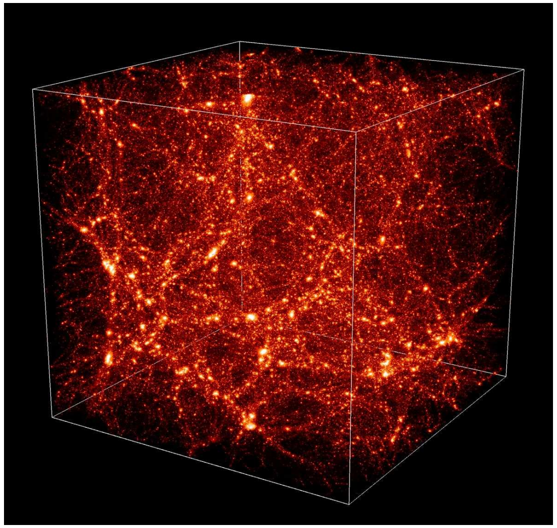
- Rotation curves in spirals
- Velocity dispersion in dwarf spheroidals
- The central part of the halo needs prescriptions:
  theoretical cosmology gives a range for systematics NFW $\rho \propto r^{-1}$, Moore $\rho \propto r^{-1.5}$



.

Central profi le unknown, partially due to a poor resolution in N-body simulations ($\sim 10^6 M_\odot$), and:

- Effect of baryon condensation in the central regions ? Black hole ? Spikes ? (Gondolo, Silk (1999))
  $\gamma \longrightarrow \gamma_{\rm spike}(9-2\gamma)/(4-\gamma)$



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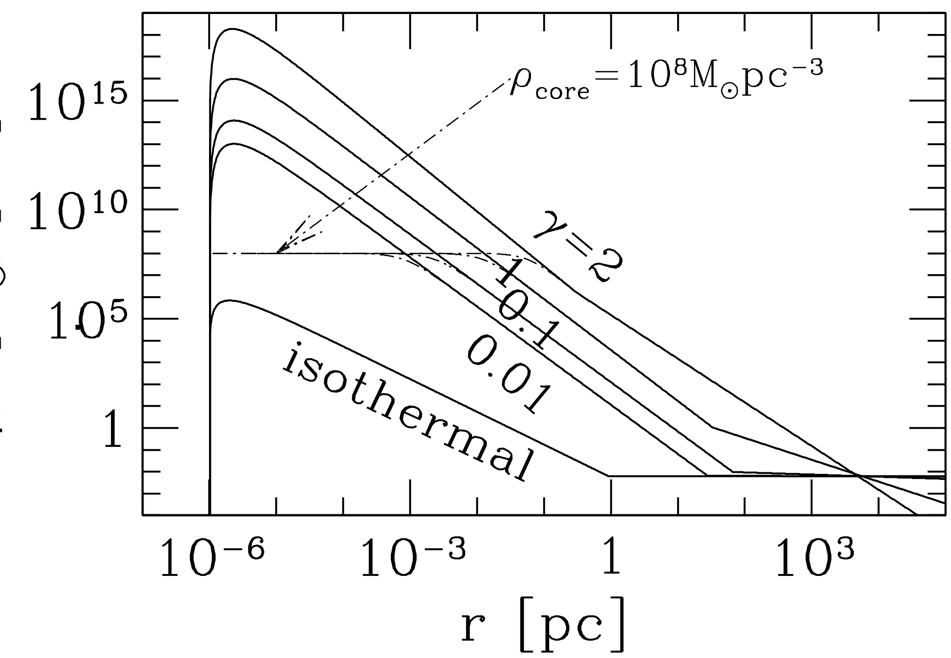

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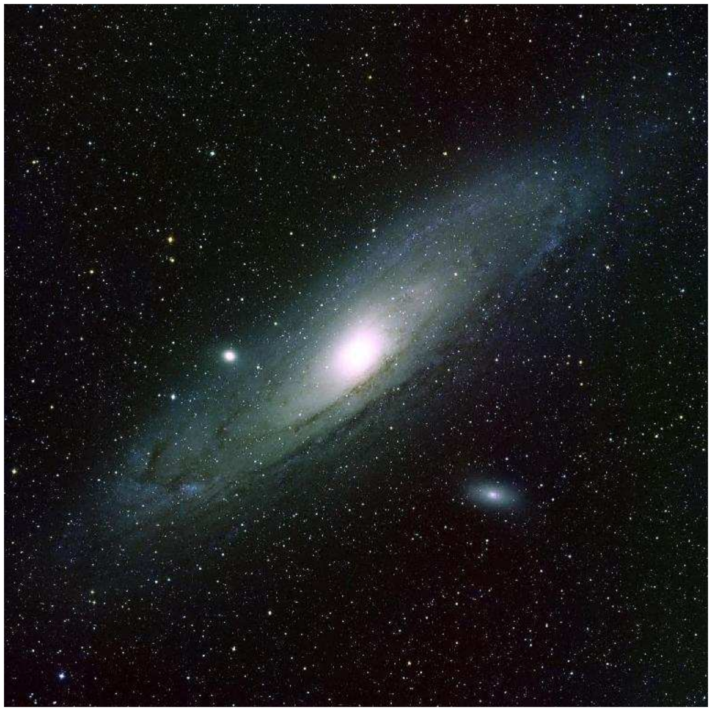
The example of M31

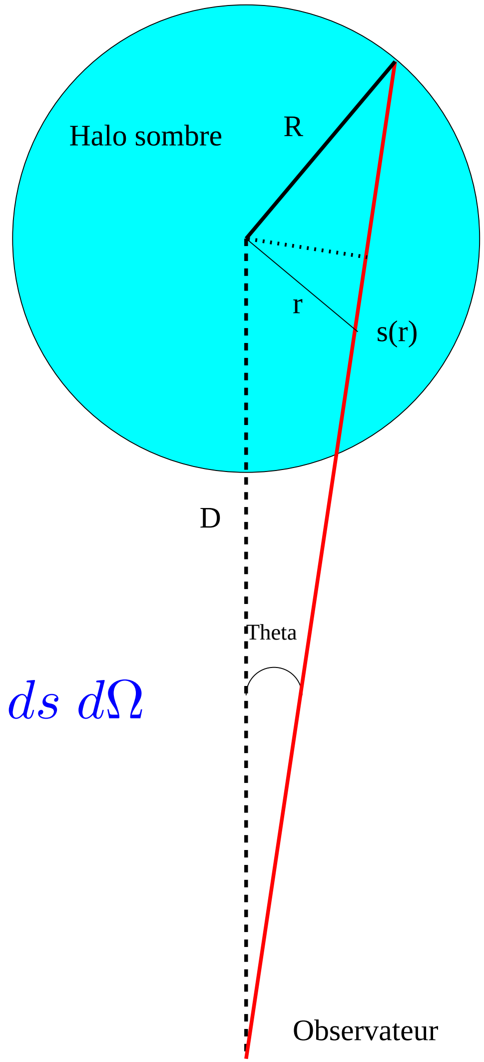
In addition to SUSY quantities, we have to compute the **astrophysics part :**

(Reminder $\phi_\gamma \propto \frac{<\sigma v>}{{m_\chi}^2} \times \Sigma(\theta)$)



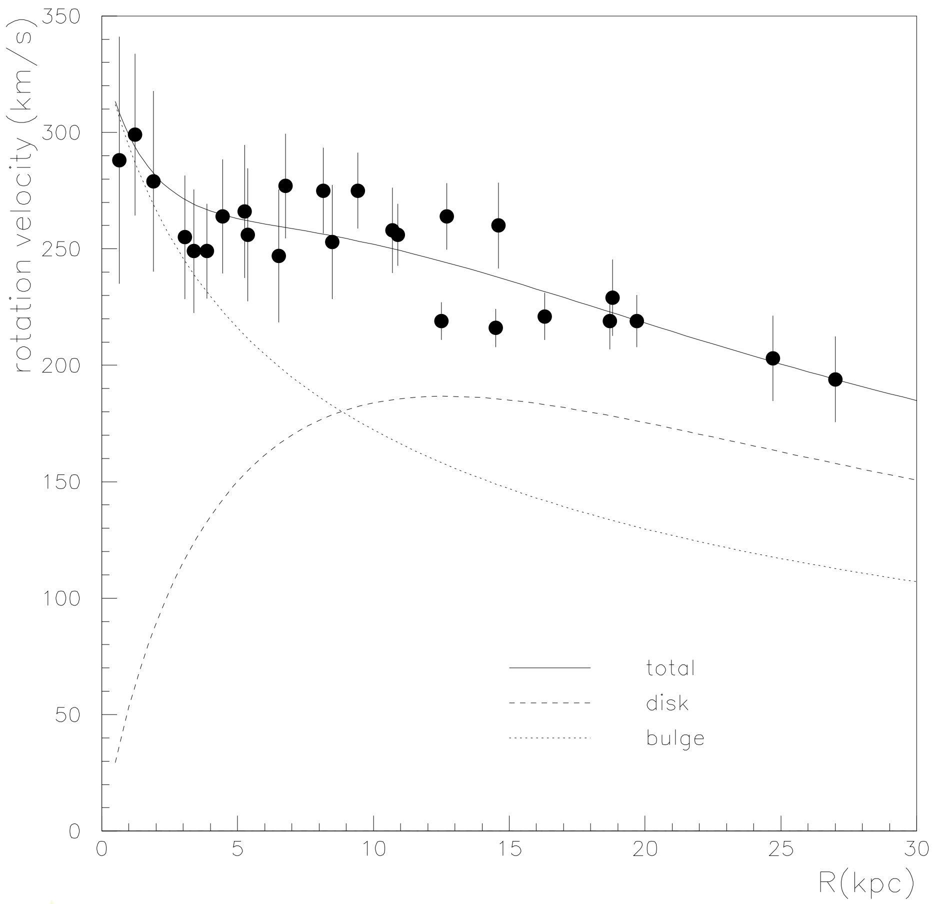
Spherical halo :

$$\Sigma(\theta) \equiv \int_{\textbf{visée}} \int_\Omega \rho^2(s)\, ds\, d\Omega$$



Braun (1991): M31 without DM

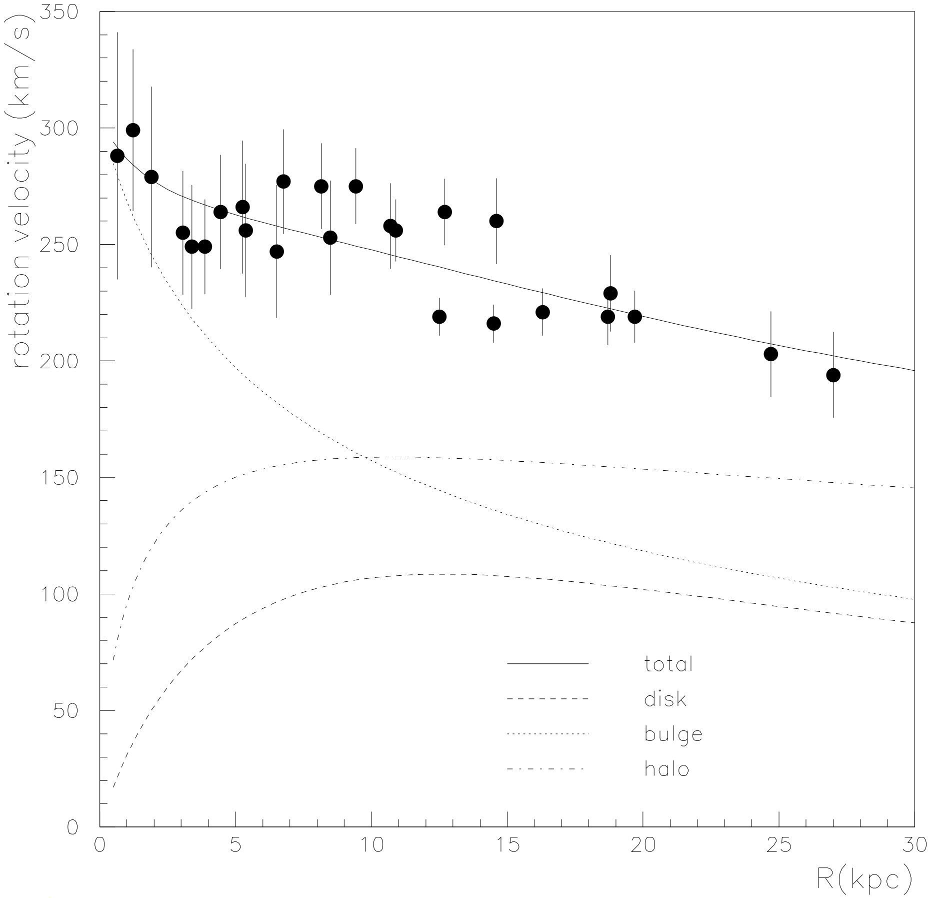
Halo contribution for M31 :



Braun uses M/L too high wrt to synthetic stellar models (6.5 and 6.4 for bulge and disc) $\longrightarrow$ with more reasonable $(M/L)_{\rm disc}$ and $(M/L)_{\rm bulge}$ an NFW can be added

Adding an NFW DM halo

Halo contribution for M31 :



Best fit for an NFW (M/L 3.5:3 bulge:disc) :

$$\Sigma = 3 \times 10^{19} \mathrm{GeV}^2 \mathrm{cm}^{-5}$$

compare with $M^2/R^3/D^2 \approx 1.6 \times 10^{19} \mathrm{GeV}^2\ \mathrm{cm}^{-5}$ (Falvard *et al.*, 2003 – ok with Widrow *et al.*, 2003)

On the astrophysical uncertainties

- On one hand, **predictions may vary over 2-4 orders of magnitude** due to astrophysical uncertainties
- One the other hand, detection could provide information on the dark matter distribution in galaxies
- Anyhow, **this points to a more fundamental issue: we still don't know much about galaxy formation** ...

Spectral information

- The spectral information is **crucial for identifying the origin of emission**.
- Different candidates can result in different spectral features:
  - SUSY: annihilating mainly to heavy quarks and gauge bosons: fragmentation (hadronic) processes + lines
  - ED allows annihilation to leptons : harder spectra

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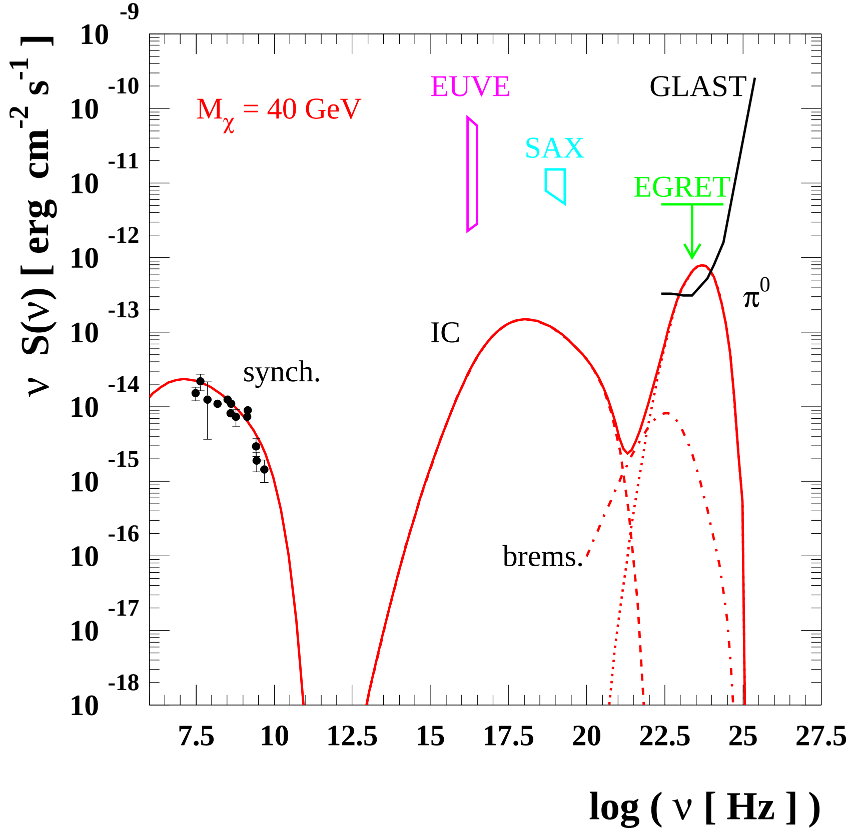
$\Longrightarrow$ For the sake of consistency, **should include IC and synchrotron emission** of charged particles produced in annihilations (marginally done in the literature). Contributions could be relevant in certain cases, and **a multi-wavelength analysis is necessary**.

Spectral information

Colafrancesco et al (2005): Coma



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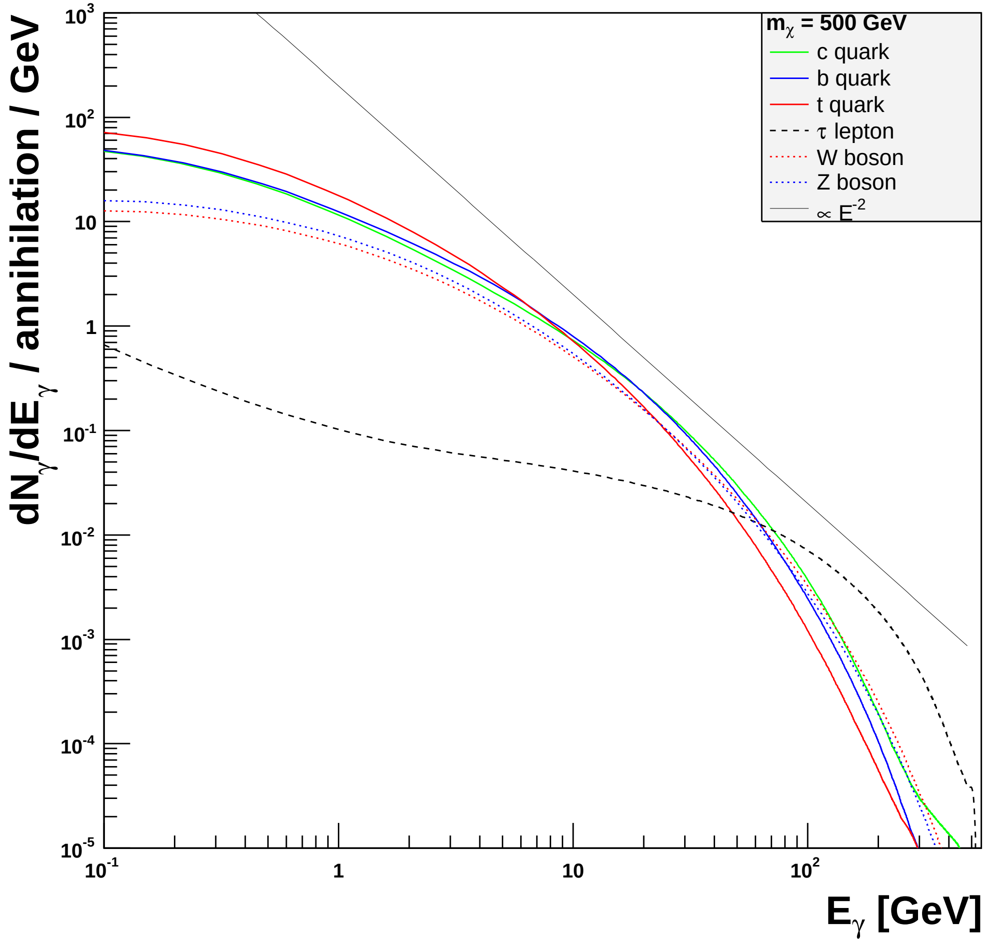
The continuum emission: Galactic Centre ?

Fragmentation processes : $\pi^0 \longrightarrow \gamma\gamma$

- Already hunted !
  IACT (HESS, MAGIC, VERITAS, CANGAROO, phase II)
- Degeneracy of fi nal states
- **Can mimic standard astrophysical processes** : diffi cult to disentangle
- **Find sources free of hadronic processes** !



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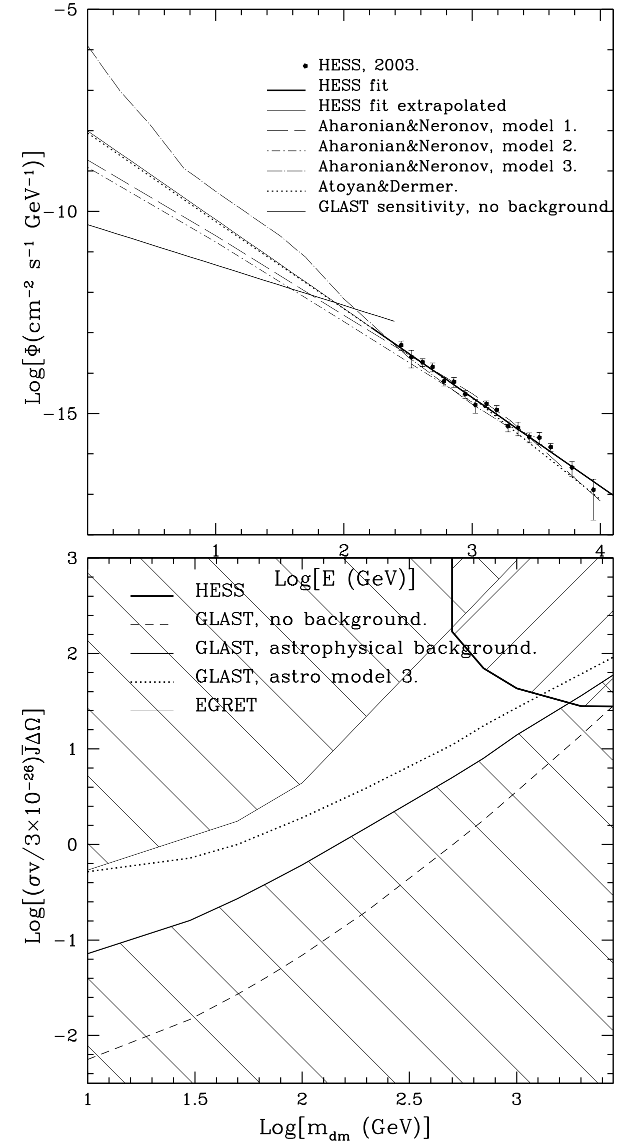
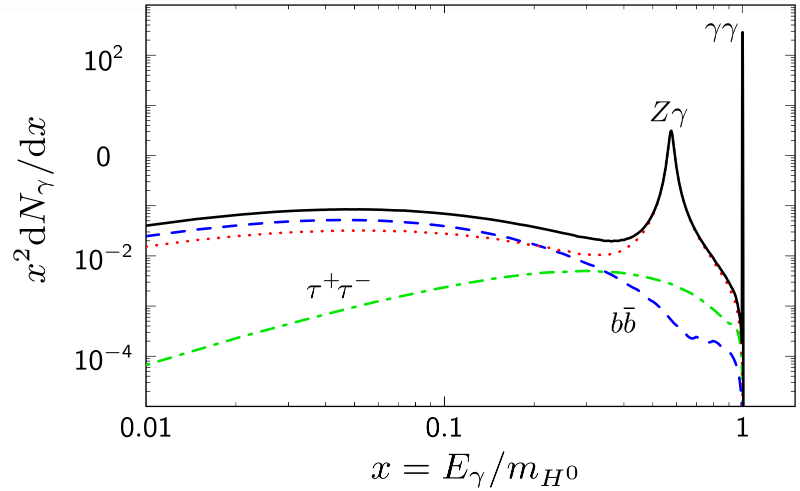
Zaharijas, Hooper (2005): GLAST vs HESS limits

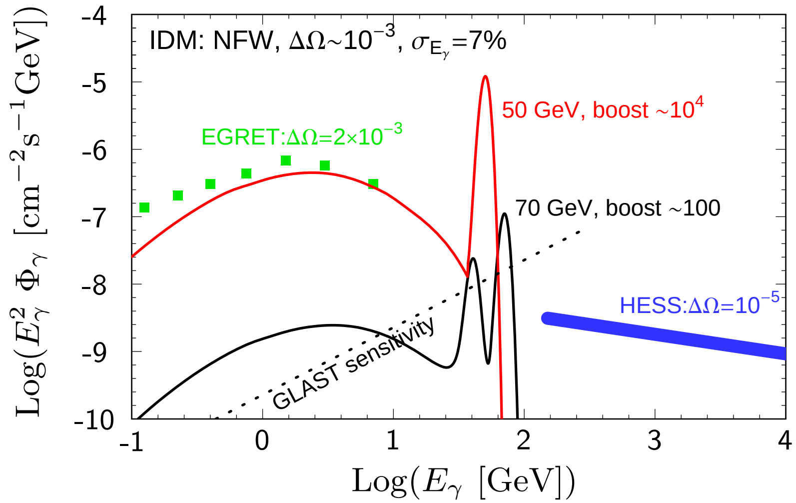


The monochromatic emission

$$\chi\chi \longrightarrow \gamma\gamma,\ \gamma Z$$
$$E_\gamma = m_\chi,\ (4m_\chi{}^2 - m_Z^2)/4m_\chi$$

- Second order processes: low fluxes ($\sim 10^{-2} - 10^{-4}$ compared to the continuum)
- unambiguous signatures, and the same in all sources





Gustafsson et al (2007): IHD model

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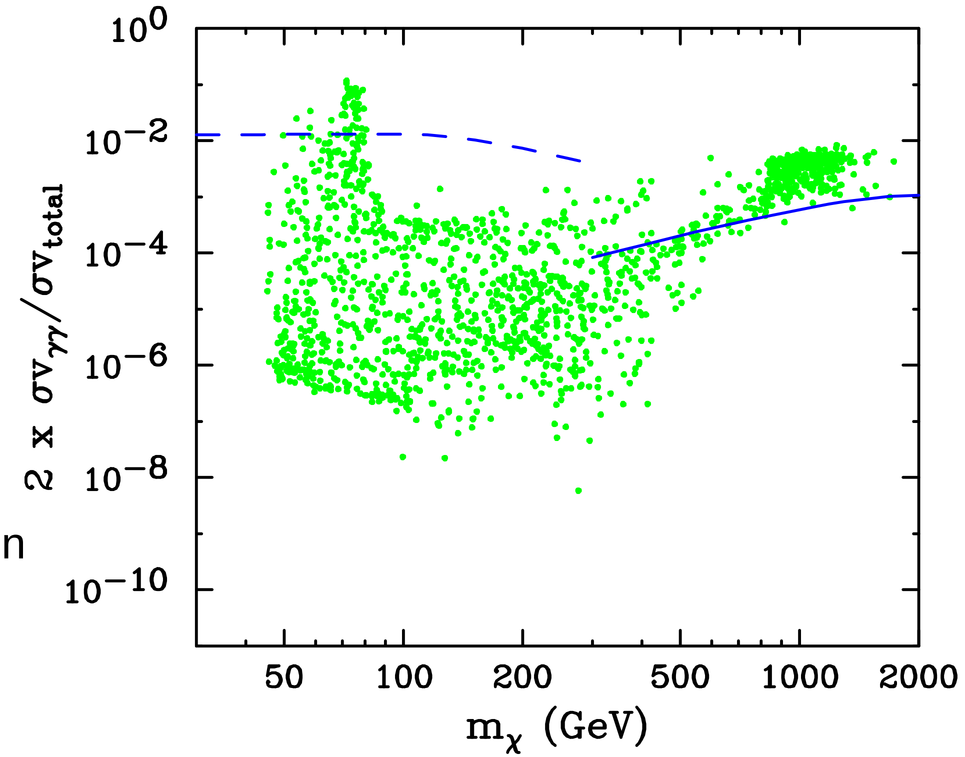


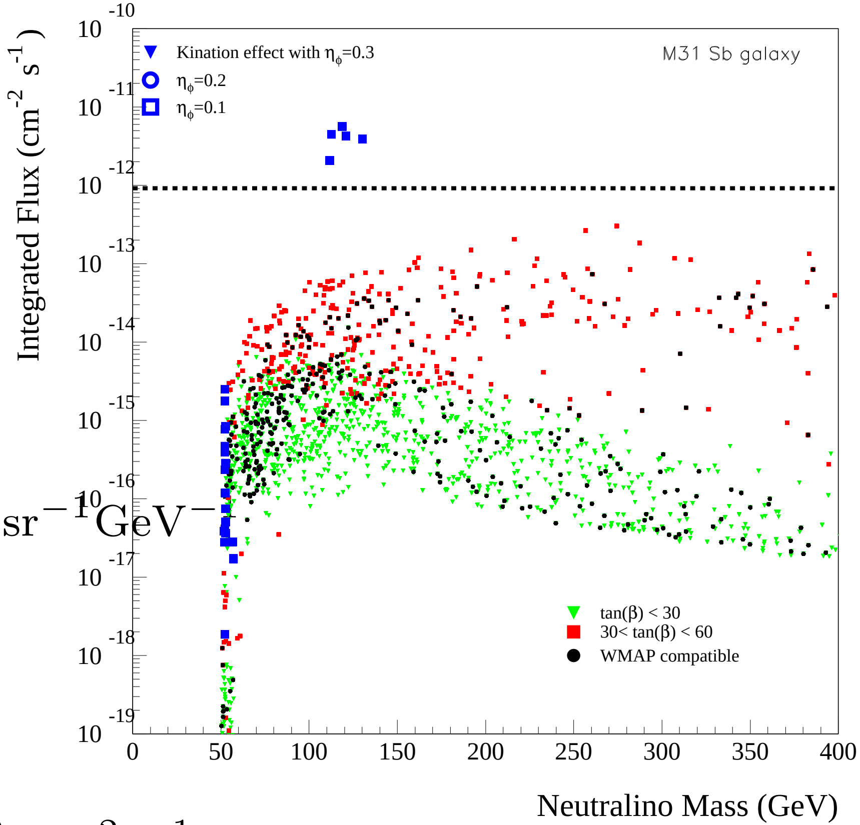
Compare to foregrounds !

A basic example, with a toy telescope

- Threshold : 50 GeV
- Energy resolution $\sim 20\%$
- Angular resolution 0.1°
- Effective area $\mathcal{A}(E) = \mathrm{cst} = 2\times 10^4 \mathrm{m}^2$

Foregrounds: the example of the (still unknown) EGB (Sreekumar et al, 1998)

$$\frac{d\Phi_{\mathrm{eg}}}{dE\,d\Omega} \approx 1.6\times 10^4 \left(\frac{E}{0.1\ \mathrm{GeV}}\right)^{-2.1} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}$$



To have $N_\sigma \gtrsim 3$ with 50 hrs of observation, fluxes must be greater than:

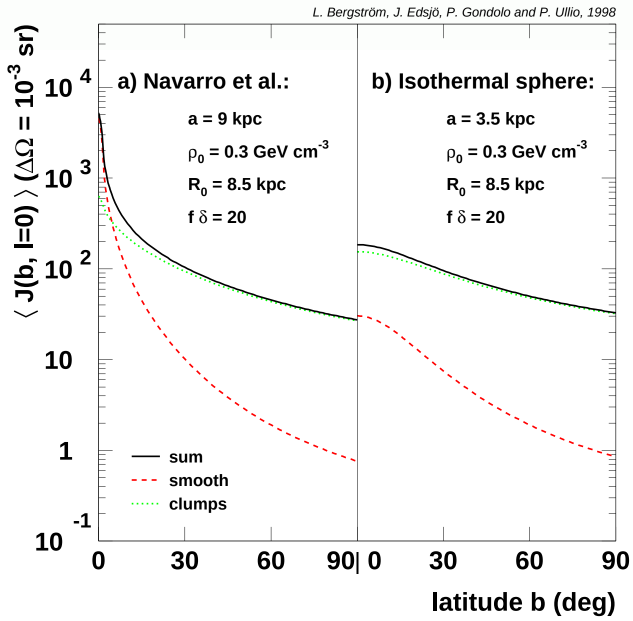
$$\Phi(>50\,\mathrm{GeV}, 0.1^o) \gtrsim \Phi_{\mathrm{min}} \approx 1.2\times 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

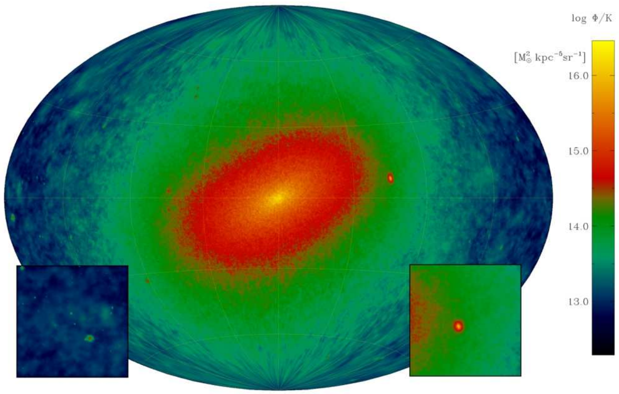
$$\Phi(>50\,\mathrm{GeV}, 0.05^o) \gtrsim \Phi_{\mathrm{min}} \approx 3.7\times 10^{-14}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Clumpiness: resolved objects / boost factors ?

Boost for γ-rays (studied for many years)

- **Factor to the smooth flux** which depends on the angle between GC direction and line of sight (*cf.* Bergström et al, 1998) ; main effects at high latitude regions (see fi gure)
- Very small additional contribution to the smooth flux in the GC direction (*cf.* Stoerh et al (2004), Berezinsky et al (2003-2007))
- Statistical M-C analysis by Bi (2006), Pieri et al (2007)
- **A very few objects** could perhaps be resolved **with GLAST** towards the anti-centre (Diemand et al, 2006 | see fi gure)





Sources: summary

- **GC (and other spiral/elliptical galaxies)**
  - Line perhaps reachable: clear signature
  - continuous emission diffi cult, because of many backgrounds
- **Dwarf spheroidals**
  - γ-rays unexpected from standard processes: could be clear signatures
  - But, flux predictions too low at the moment
  - Deserve observations anyway
- **Clumps**
  - Quizas, quizas, quizas ... Large fi eld of view survey
- **Clusters**
  - Marginally studied (Colafrancesco et al)

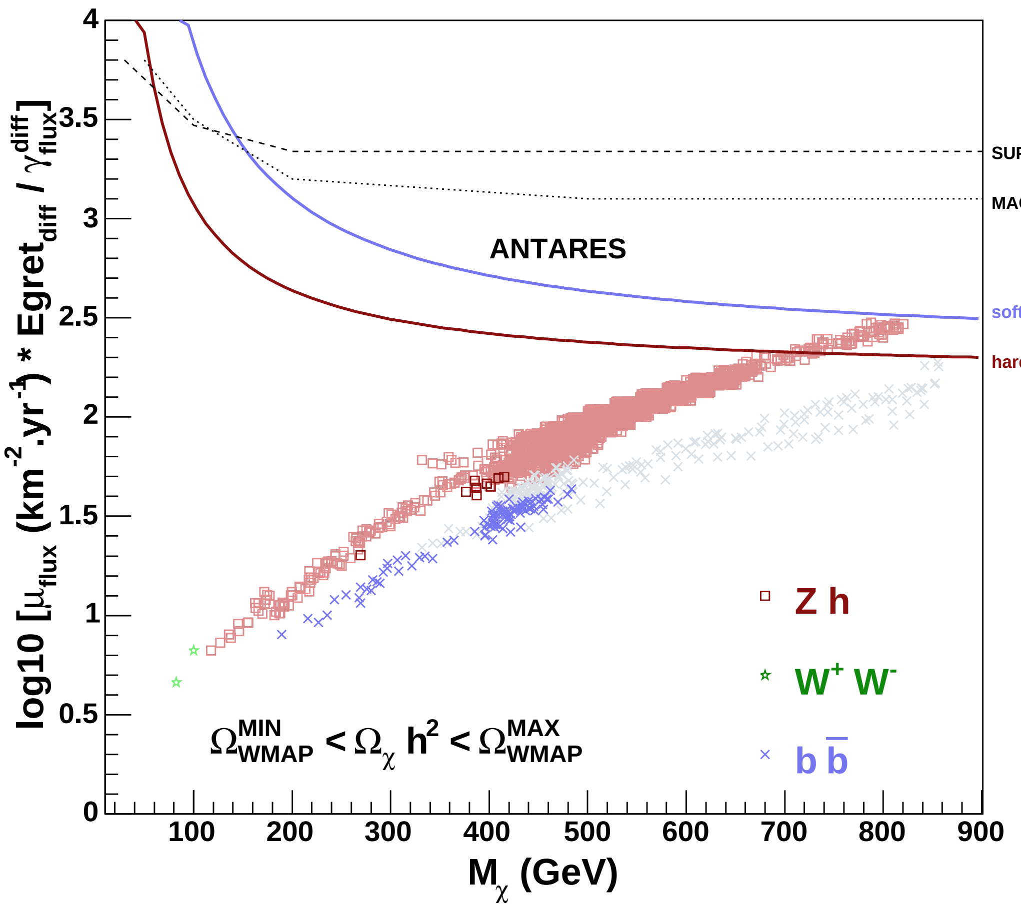
Neutrinos

- Neutrinos are **produced in fragmentation** (hadronic) processes in the same way as gamma-rays (charged pions)
- Roughly **same flux expectations as for gamma in galaxies**, but experimental sensitivities much lower ($\mathcal{A}_\gamma \sim 10^4 \mathrm{m}^2$ versus $\mathcal{A}_\nu \sim 10^{-4} \mathrm{m}^2$)
- **Additional targets**: can escape the centres of massive objects due to the weakness of interactions (stars—Sun, planets—Earth)
- **neutrino lines naturally arise in ED theories + annihilation in leptons $\Longrightarrow$ hard spectra**

The Galactic Centre and other galaxies: why not ?

Why not ?

- Observed gamma-ray fluxes can translate into upper bounds for neutrino fluxes (neglecting absorption) – Bertone et al (2005)
- e.g. EGRET: $\phi_\nu^{\max} = \phi_\nu^{\rm DM} \times \frac{\phi_{\rm EGRET}}{\phi_\gamma^{\rm DM}}$
- Unreachable for present experiments



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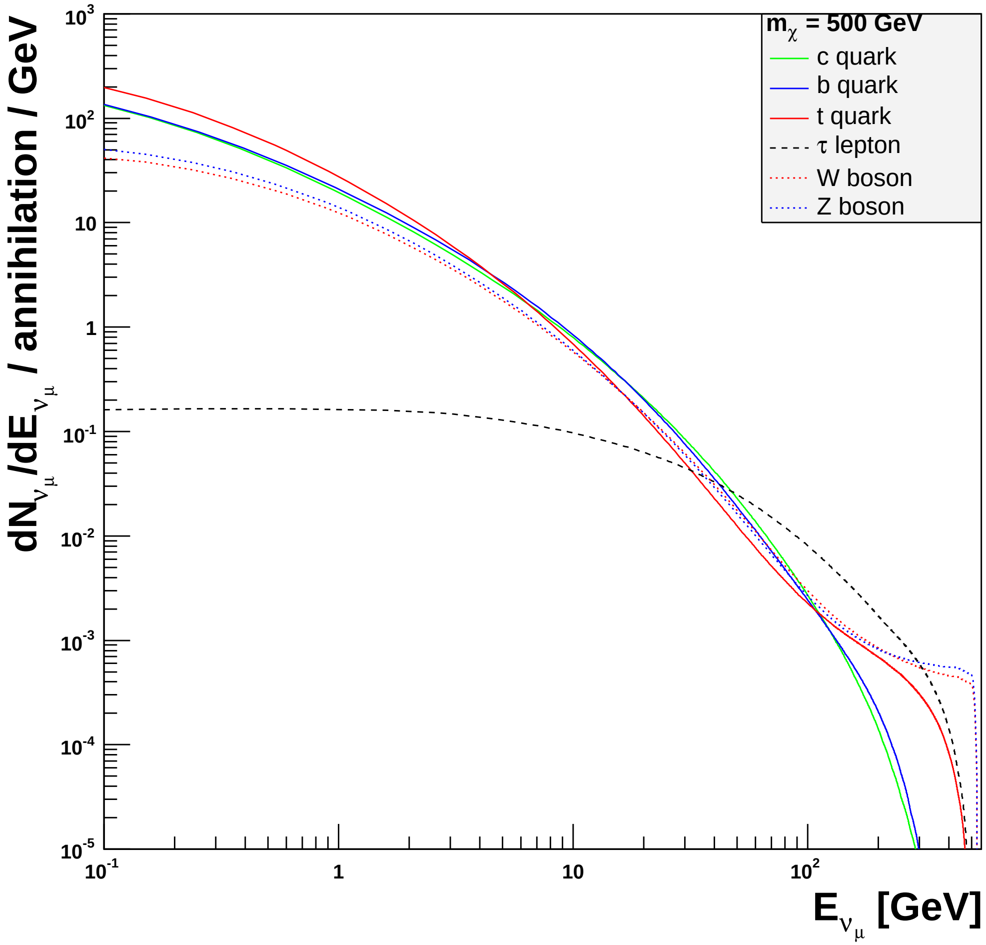
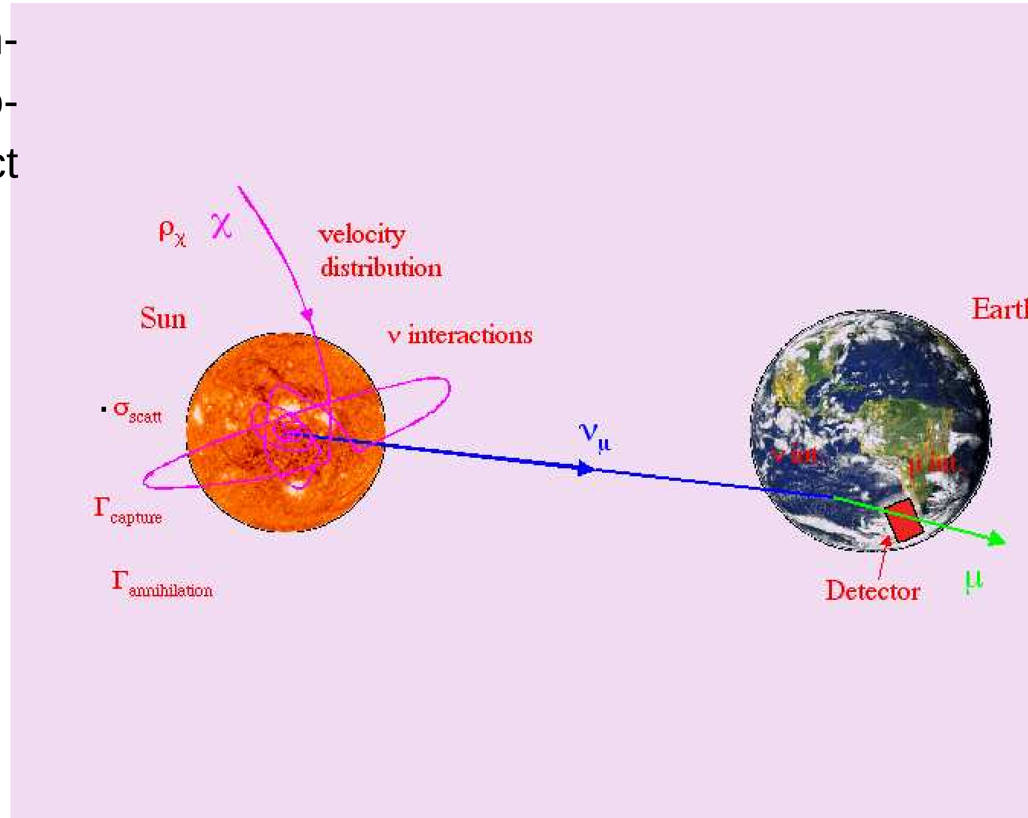


The Sun and the Earth

WIMPs may **scatter off nuclei** (favoured in massive and dense objects) and loose enough energy to be **gravitationally captured**. The evolution of the number of WIMPs inside the object is:

$$\frac{dN}{dt} = C - C_A N^2 - C_E N$$

Capture | Annihilation | Evaporation



The annihilation rate reads:

$$\Gamma_A(t) = \frac{\delta}{2} C_A N^2(t)$$

$$\Gamma_A(t) = \frac{\delta}{2} \tanh^2 \frac{t}{\tau} \; , \quad \tau = \sqrt{C \times C_A}$$

τ is the timescale for equilibrium to occur

WIMP capture in the Sun/Earth

The capture rate depends on:

- The local WIMP density $\rho_\odot/m_\chi$
- The local velocity dispersion $\bar{v} = \sqrt{< v^2 >}$ (low part of the distribution – contrary to direct detection)
- The elastic scattering cross-section off nuclei $\sigma_{\rm el}$
- The composition profi le of the object of interest

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{C_\odot P_{\odot,\nu}(E_\nu)}{2\times 4\pi D_\odot^2} \sum_{\rm fin} B_{\rm fin} \left(\frac{dN_\nu}{dE_\nu}\right)_{\rm fin}$$

Gould (1991):

$$C_\odot \simeq 3.35 \times 10^{20} {\rm s}^{-1} \left(\frac{\rho_\odot}{0.3\,{\rm GeV/cm^3}}\right) \left(\frac{270\,{\rm km/s}}{{\rm v}_\odot}\right)^3 \left(\frac{\sigma_{\rm el}}{10^{-6}\,{\rm pb}}\right) \left(\frac{100\,{\rm GeV}}{{\rm m_{wimp}}}\right)^2$$

Composition: $\sim 65\%$ ^{1}H et $\sim 35\%$ ^{4}He (no spin for ^{4}He):
$\sigma_{\rm el} = \sigma_{\rm SI}^{\rm H} + \sigma_{\rm SD}^{\rm H} + 0.067\sigma_{\rm SI}^{\rm He}$

Annihilation final states in very dense media

- Final states are **produced in a very dense region**: are they **able to decay before they get absorbed** ?
- contributions from light quarks can be neglected
- **the hardest spectra would come from decays of muons and tau’s**
- Need a precise computation of absorption length inside the medium

Energy loss in the Earth

In the Earth, the energy loss equation is the Bethe-Bloch equation (+ radiative correction $\gtrsim 500\mathrm{GeV}$)

$$
\begin{aligned}
\frac{dE}{dx} &= K\, z^2\, \frac{Z}{A}\frac{1}{\beta^2}\Big[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \ln\frac{hbar\omega_p}{I} - \ln\beta\gamma + \frac{1}{2}\Big] \\
K &= 4\pi N_A r_e^2 m_e c^2 \approx 0.3\mathrm{MeV\,cm^2\,mol^{-1}} \\
T_{\max} &= \frac{2m_e c^2\beta^2\gamma^2}{1+2\gamma m_e/M+(m_e/M)^2} \\
\hbar\omega_p &= 28.8\sqrt{\rho < Z/A >}\,\mathrm{eV}
\end{aligned}
$$

For muons/taus in the centre of the Earth (liquid iron with $\rho \sim 13$ g/cm^3), the minimum/maximum values reads:

$$
\begin{aligned}
\left(-\frac{dE}{dt}\right)^{\mathrm{Earth}}_{\mathrm{min}} &\approx 5.7\times 10^8\mathrm{GeV/s\ for\ muons} \\
\left(-\frac{dE}{dt}\right)^{\mathrm{Earth}}_{\mathrm{max}} &\approx 9.3\times 10^8\mathrm{GeV/s\ for\ taus}
\end{aligned}
$$

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$$K = 4\pi N_A r_e^2 m_e c^2 \approx 0.3\mathrm{MeV\,cm^2\,mol^{-1}}$$

$$T_{\rm max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

$$\hbar\omega_p = 28.8 \sqrt{\rho < Z/A >}\,\mathrm{eV}$$

Now compare *stopping* time with *decay* time:

$$\tau_{\rm stop} = \frac{E}{dE/dt}$$

$$\gamma\tau_{\rm dec} = \frac{E}{m}\tau_{\rm dec}$$

$$\Longrightarrow \begin{cases} \left(\frac{\tau_{\rm stop}}{\tau_{\rm dec}}\right)^{\rm Earth} \lesssim 8.4 \times 10^{-5} \text{ for muons} \\ \left(\frac{\tau_{\rm stop}}{\tau_{\rm dec}}\right)^{\rm Earth} >> 1 \text{ for taus} \end{cases}$$

Energy loss in the Sun

For charged leptons interactions in the core of the sun, the Bethe-Block equation has to be modifi ed (plasma physics):

$$-\frac{dE}{dx} = -\frac{e^2}{4\pi\epsilon_0}\frac{\omega_p^2}{(\beta c)^2}\ln\left[\frac{\Lambda m_e c^2\gamma\beta^2}{\hbar\omega_p}\right]$$

ω_p is the plasma frequency

or muons/taus in the centre of the Sun (70% H and 30% He, $\rho \sim 148$ g/cm^3),
he minimum/maximum values reads:

$$\left(-\frac{dE}{dt}\right)^{\rm Sun}_{\rm min} \approx 7.5\times 10^9 {\rm GeV/s \; for \; muons}$$

$$\left(-\frac{dE}{dt}\right)^{\rm Sun}_{\rm max} \approx 1.4\times 10^{10} {\rm GeV/s \; for \; taus}$$

$$\Longrightarrow \begin{cases} \left(\frac{\tau_{\rm stop}}{\tau_{\rm dec}}\right)^{\rm Sun} \lesssim 6.4\times 10^{-6} \text{ for muons} \\ \left(\frac{\tau_{\rm stop}}{\tau_{\rm dec}}\right)^{\rm Sun} >> 1 \text{ for taus} \end{cases}$$

Heavy quarks in the Sun

- Top quark will decay before any interaction, and so for massive gauge bosons ...
- but c and b could interact: need to take the energy transfer into account $\Rightarrow$ the resulting neutrinos are also affected

Neutrino interactions in the Sun

In the Sun, neutrinos experience

- Charged current interactions: damping of ν_e and ν_μ, but re-injection due to ν_τ
- Neutral current: energy losses
- Oscillations occur: vacuum + MSW

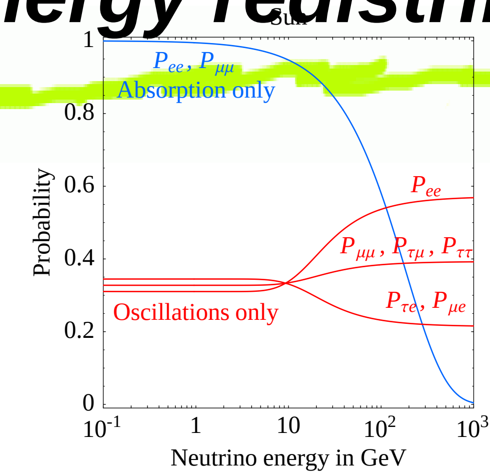
$$\sigma_{CC} \approx a \times E_\nu \quad \left(a_{\nu p} \sim 4.5 \times 10^{-39} \mathrm{cm}^2 \, \mathrm{GeV}^{-1}\right)$$

$$\sigma_{NC} \approx b \times E_\nu \quad \left(b_{\nu p} \sim 2.0 \times 10^{-39} \mathrm{cm}^2 \, \mathrm{GeV}^{-1}\right)$$

The consistent formalism is the matrix density space evolution as treated in quantum mechanics (Rafelt, Sigl & Stodolshy, 1992) – Cirelli et al (2006):

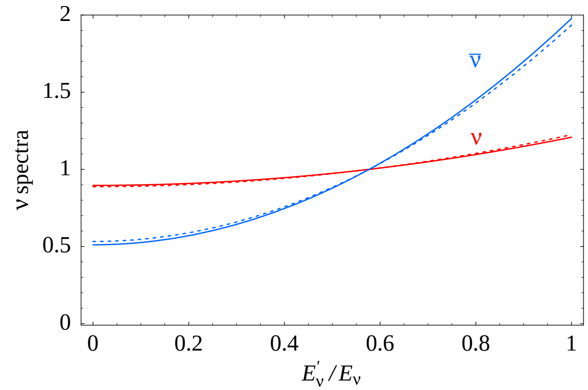
$$\frac{d\rho}{dr} = -i[H, \rho] + \frac{d\rho}{dr}|_{CC} + \frac{d\rho}{dr}|_{NC} + \frac{d\rho}{dr}|_{\mathrm{injection}}$$

Neutrino: absorption, oscillation, energy redistribution

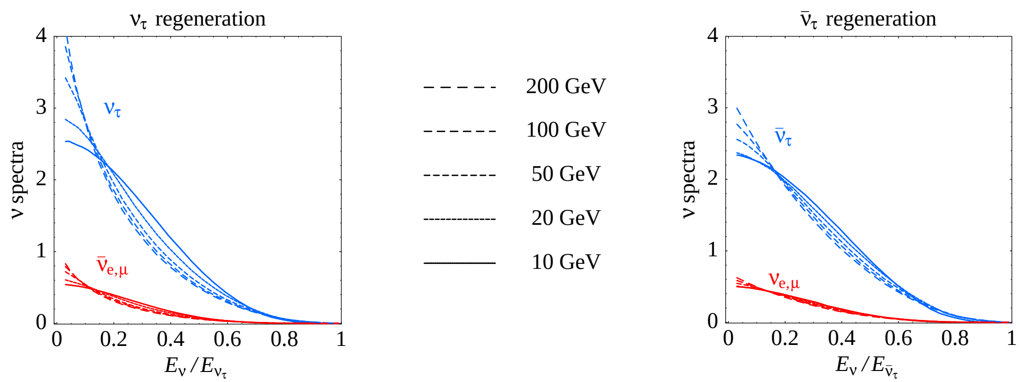


Cirelli et al (2005)

- Absorption due to CC interaction is exponential above ~ 100 GeV
- NC energy redistribution compensates the loss of neutrinos



$$\nu_\tau \longrightarrow \tau^- \quad \longrightarrow \quad X\ \nu_\tau\ (65\%)$$
$$\longrightarrow \quad e^-\ \bar{\nu}_e\ \nu_\tau\ (18\%)$$
$$\longrightarrow \quad \mu^-\ \bar{\nu}_\mu\ \nu_\tau\ (17\%)$$



From the Sun to the detector

- Same physics when crossing the Earth, but different medium (other oscillation regime, no absorption)
- Compute the muon range in order to estimate the muon flux at the detector

................In principle

$$\phi_\mu \propto E_\nu^2 \frac{dN_\nu}{dE_\nu}$$

.... but minimum ionisation below 1 TeV ...

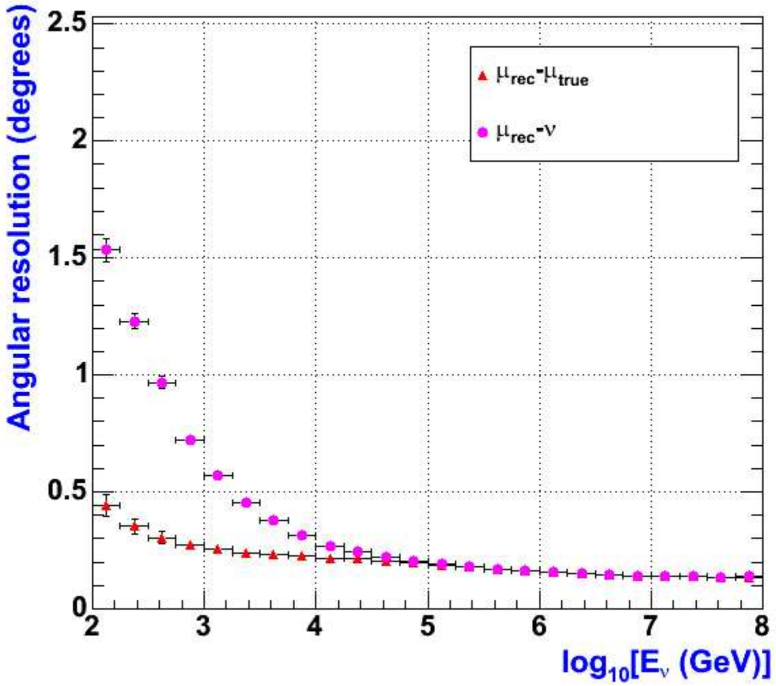
Predictions: pro and cons

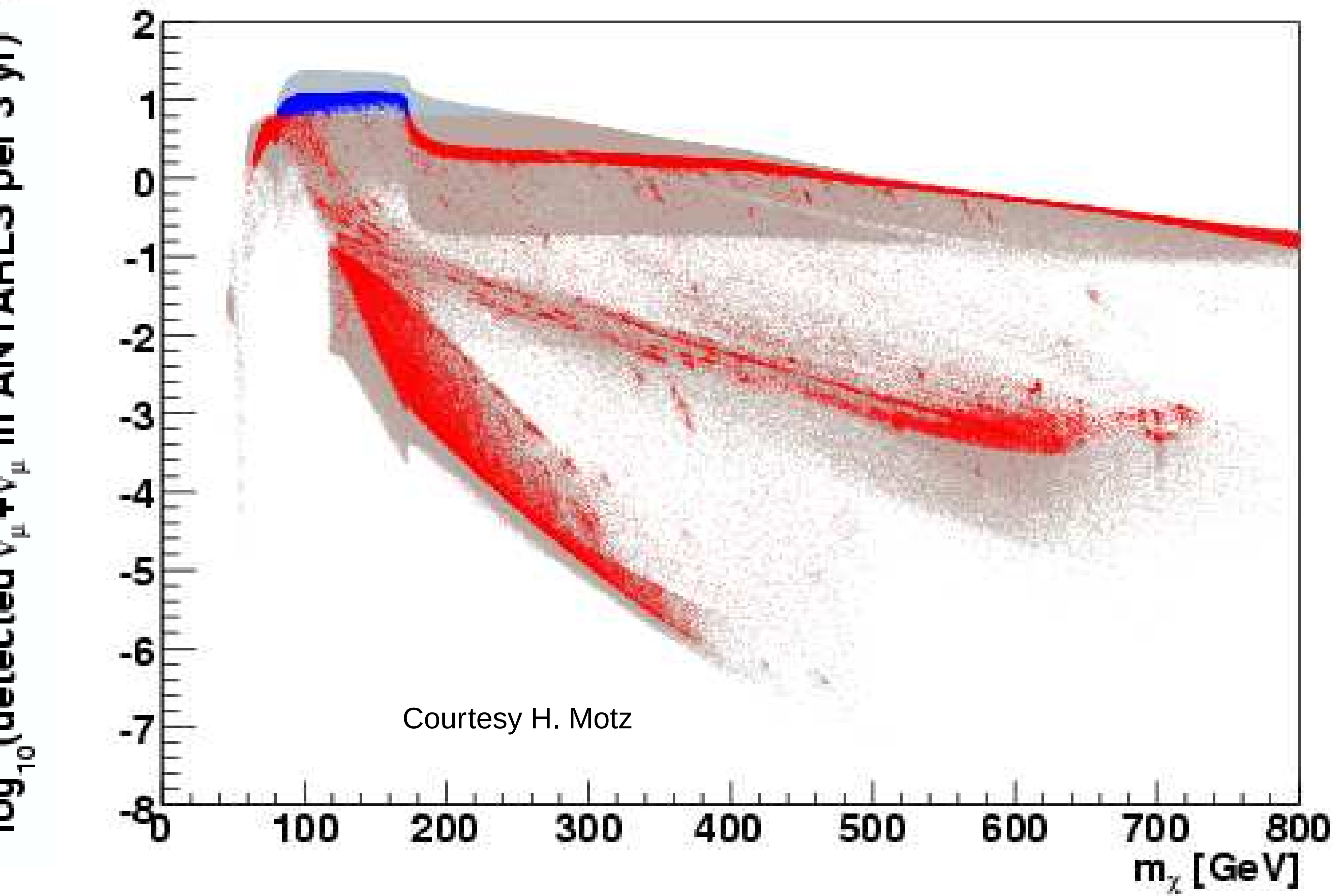
Good points:

- The source is close
- Unambiguous signature in case of detection

Bad points

- Absorption in the Sun limits the energy range to energies below ~ 150 GeV
- Bad angular resolution at such energies: diffi cult to compress the atmospheric neutrino background





log10(detected νμ+ν̄μ in ANTARES per 3 yr)
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
0
100
200
300
400
500
600
700
800
mχ [GeV]
Courtesy H. Motz

Other sources: IMBHs

For neutrinos, we need:

- high energies
- hard spectra
- high fluxes

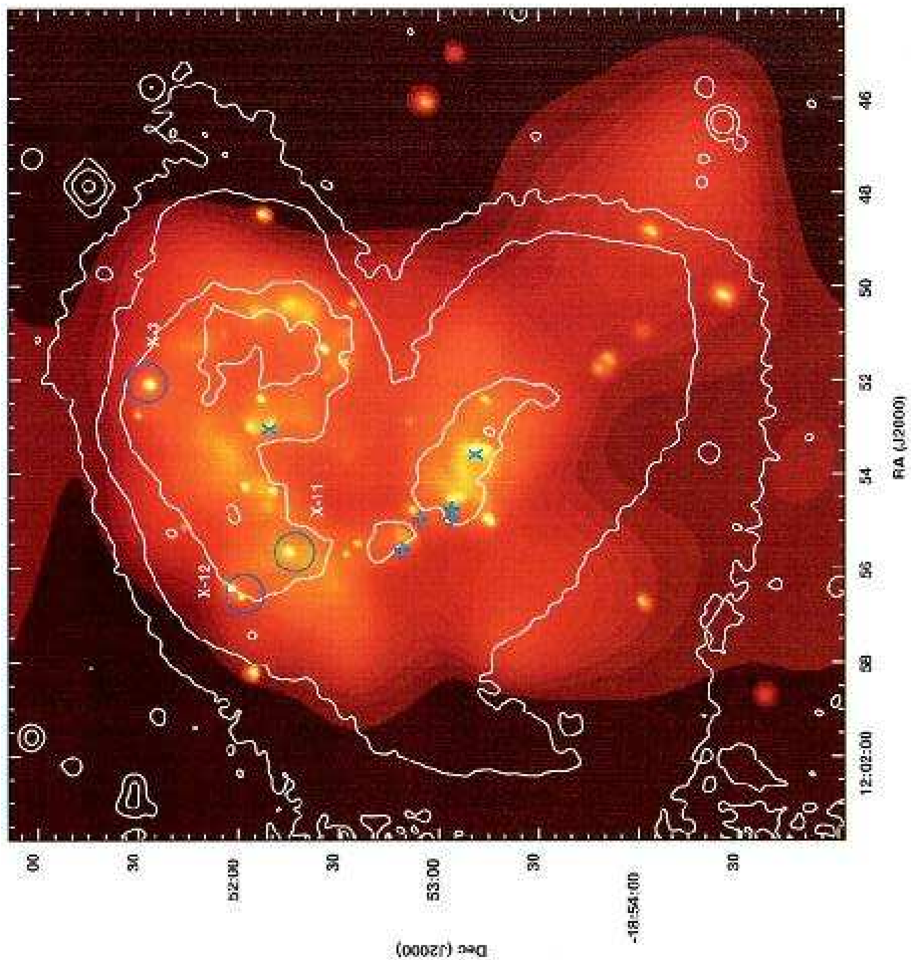
So ... what about LKP around very massive black holes ?

- annihilation in leptons allowed
- the DM density is enhanced around them: spikes
- no aborption

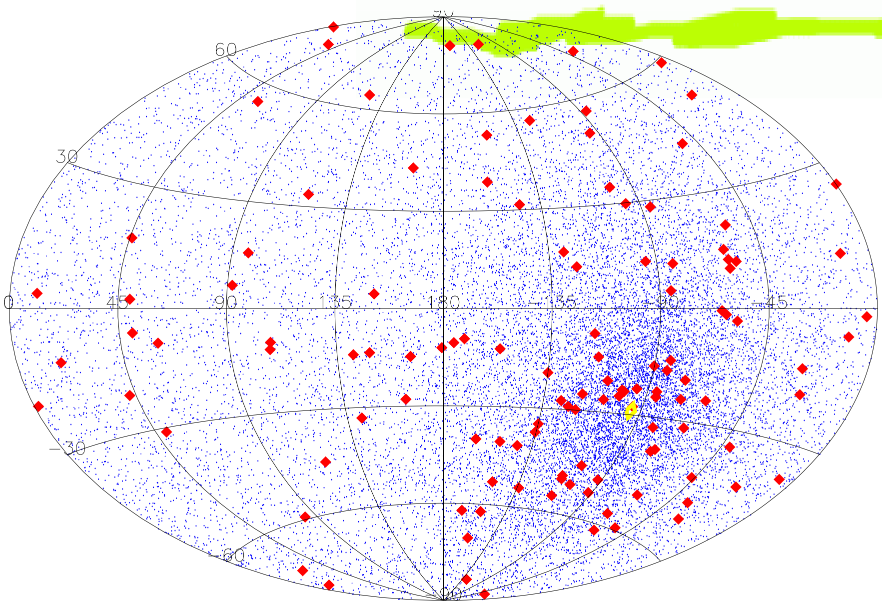
Hints for the existence of IMBHs

(review in Miller & Colbert - astro-ph/0308402)

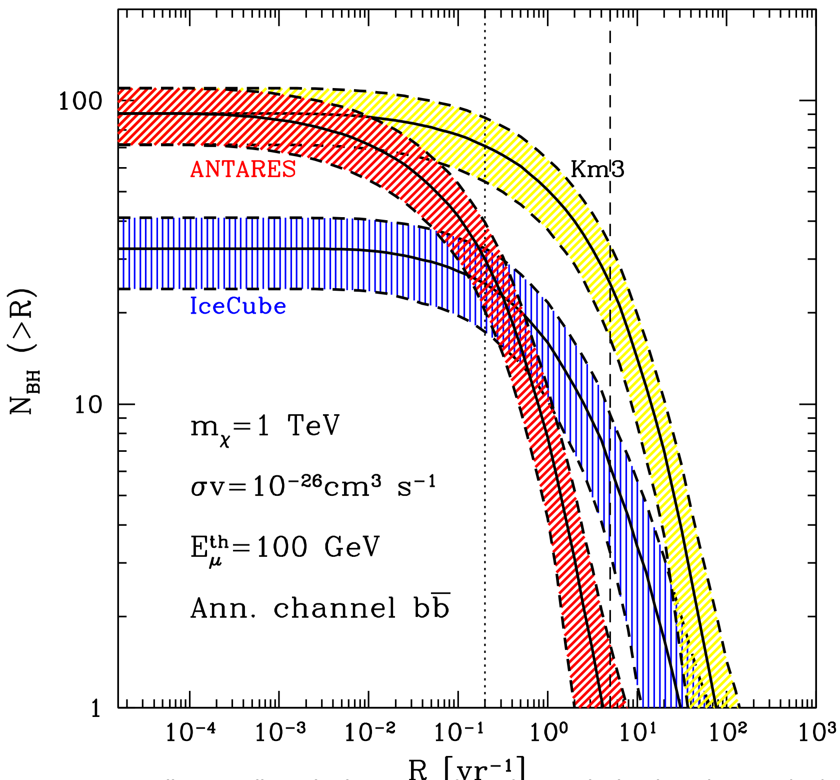
- IMBH: black hole with mass between stellar BH and supermassive BH ($20 \leq M_{IMBH}/M_{\odot} \leq 10^{6}$)
- Hints provided by detection of ultra-luminous X-ray sources (ULX) not associated with AGN
- Theoretically interesting because can be seeds for SMBHs that seemed to have formed early in the universe (1 Gyr)
- IMBHs may originate from remnants of 0-metallicity pop III stars, or from primordial gas (H_2) cooling in early-forming halos.



IMBHs & neutrinos:
Bertone's view (astro-ph/0603148)



- Reachable for ANTARES
- No absorption like in the Sun

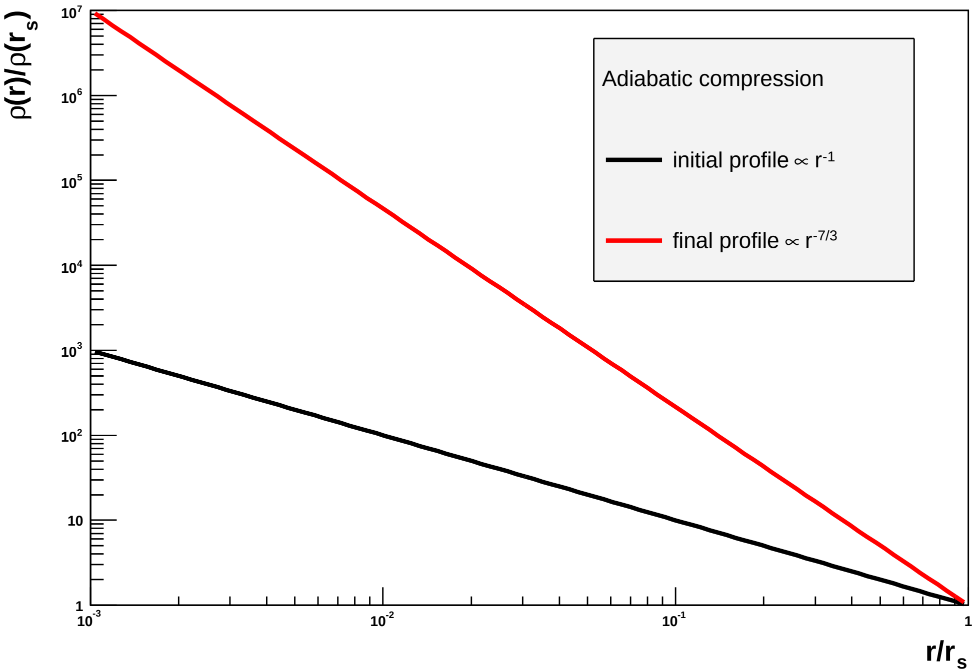


- No strong constraints from gamma-rays:
  EGRET not sensitive enough
  HESS don't know about IMBHs locations

IMBH and dark matter profile

The slow formation of a BH induces conservation of adiabatic invariants. The consequence is the compression of the density close to the BH (Gondolo & Silk, 1999). Given $\rho \propto r^{-\gamma}$

$$\boxed{\gamma_{in} \quad \longrightarrow \quad \gamma_{fin} = \frac{9-2\gamma_{in}}{4-\gamma_{in}}}$$



We defi ne the **intrinsic effective volume**:

$$\xi_{bh} \equiv \int_{V_{dm}} d^3\vec{x} \left(\frac{\rho_{bh}}{\rho_0}\right)^2$$

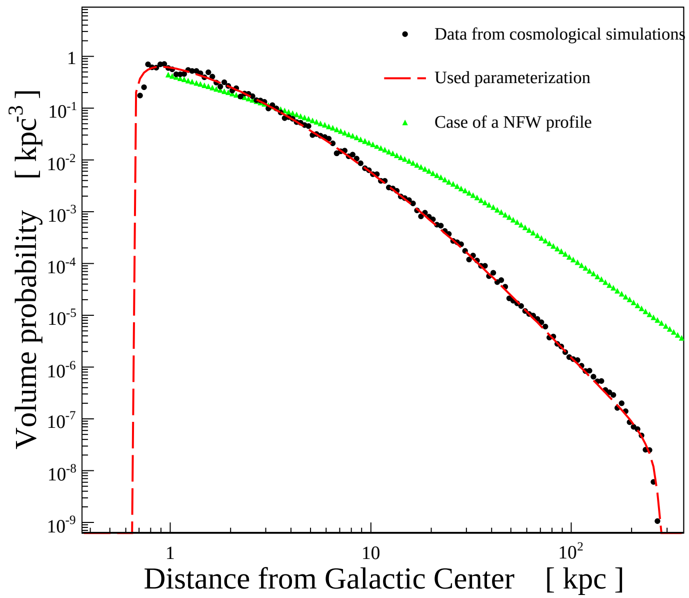
such that the **intrinsic luminosity** is:

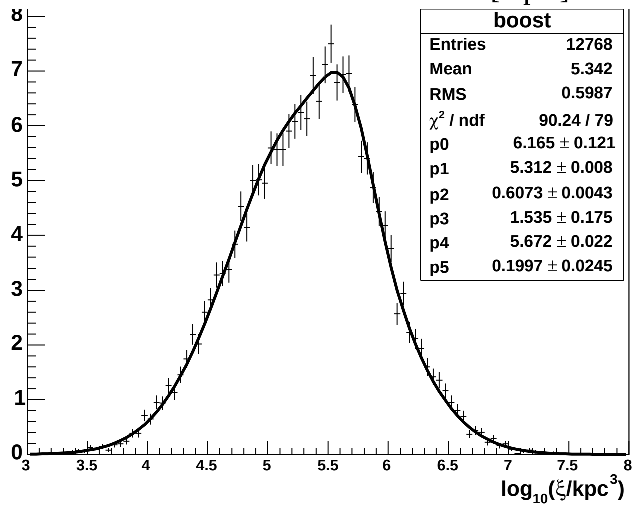
$$L_{bh} = \{S = \frac{\delta < \sigma v >}{4\pi} \left(\frac{\rho_0}{m}\right)^2\} \times \xi_{bh}$$

The Bertone, Zentner and Silk model (astro-ph/0509565)

Original idea in Zhao and Silk (astro-ph/0501625)

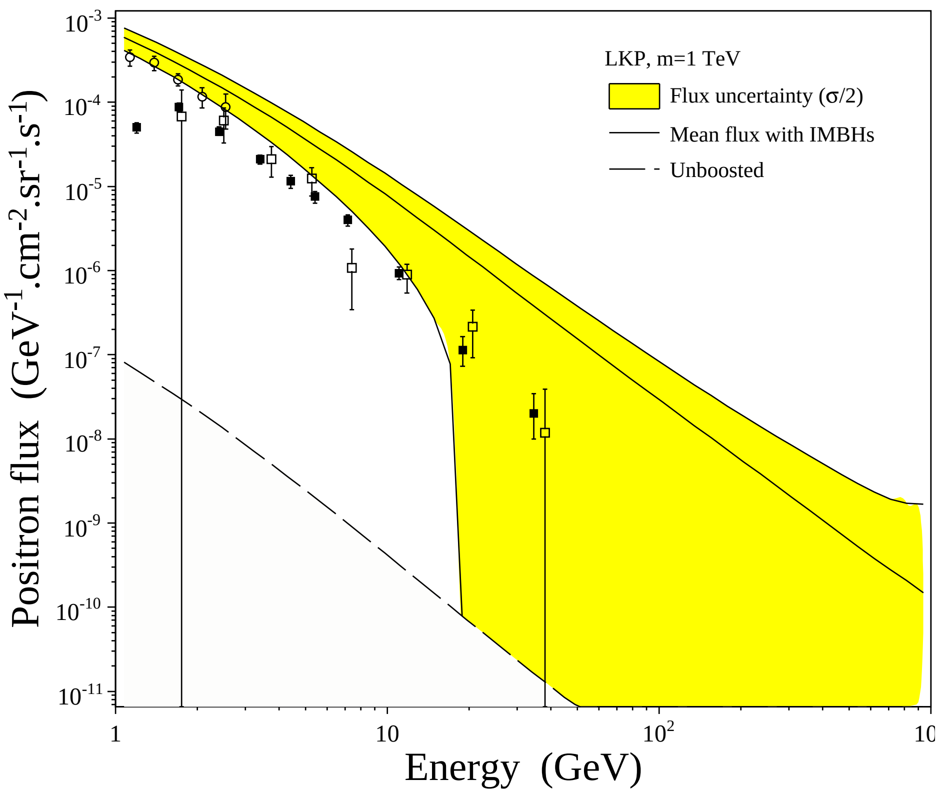
- Intermediate mass black holes (IMBHs) may populate the halo ($\sim$ 70 within $R < 20$ kpc)
- Simulations predict their space distribution and features
- **Use that for cosmic rays !**

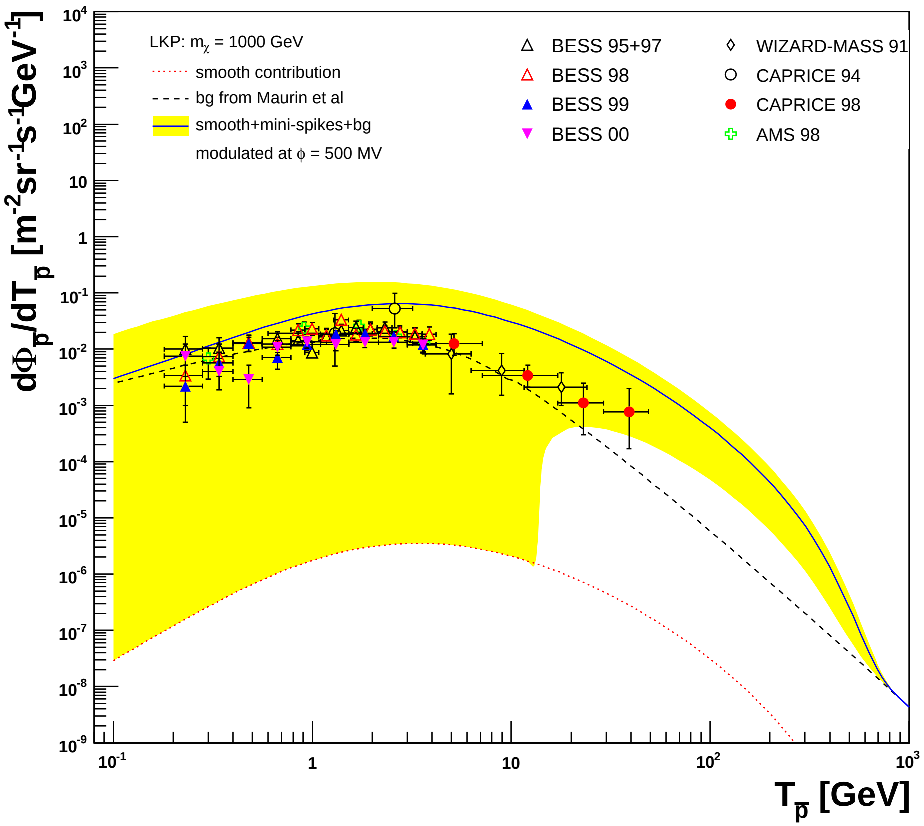




Brun et al (2007):

$e^+/\bar{p}$ fluxes for a 1 TeV LKP





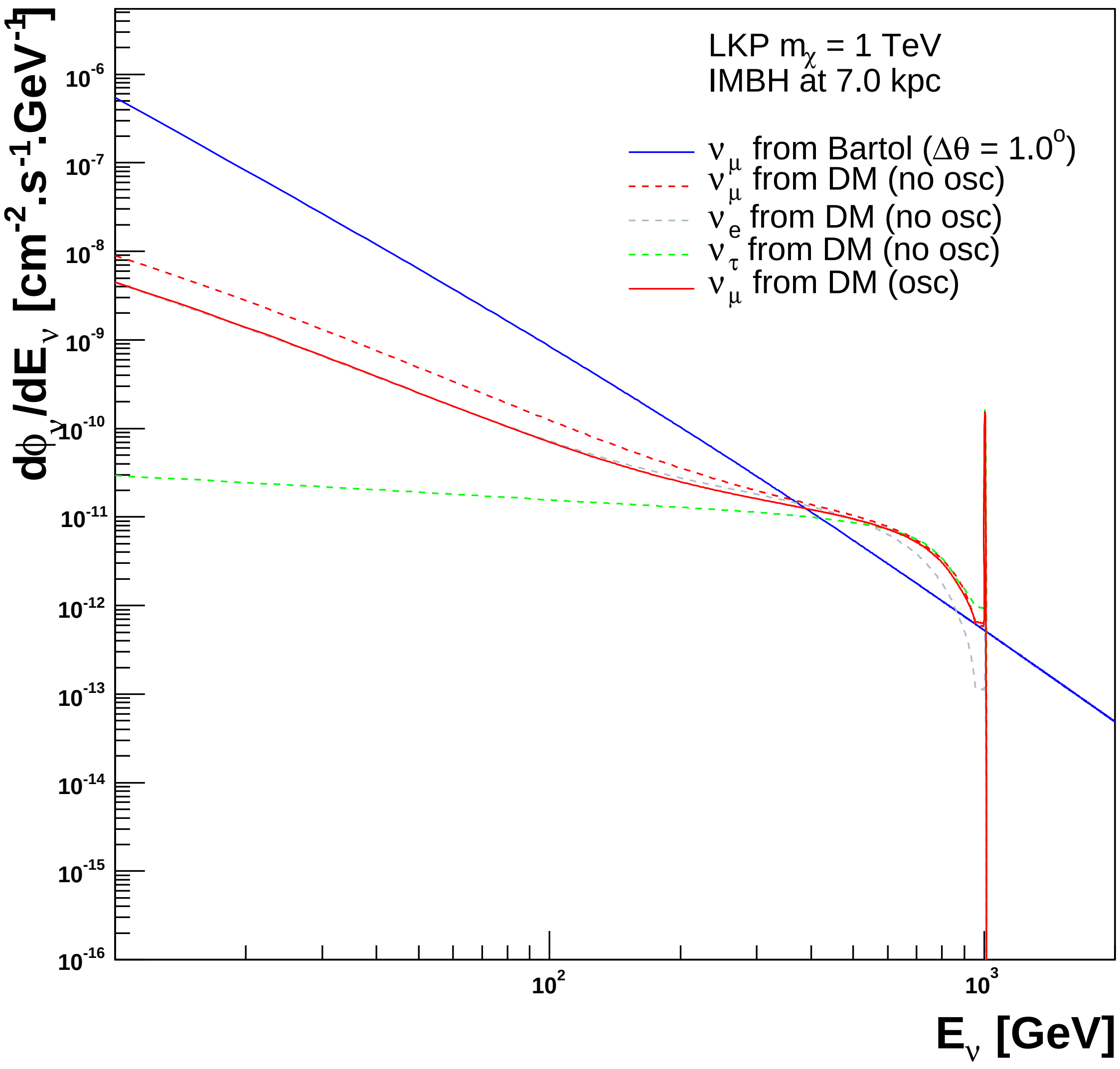
Relevant points

Keys for interpretation

- **Low energy positron data sensitive to far away regions: integrate a large number of IMBHs (energy loss dominant)**
- **Low energy anti-proton data sensitive to close regions: integrate a small number of IMBHs (no energy loss, but convective wind and spallations at low energy)**
- **Low energy positron data seem to disfavour any candidate but – heavy – LKPs**
- **LKPs affect the high energy anti-proton spectrum (no data at the moment)**
- **...The closest IMBH contribution dominates over the others !**

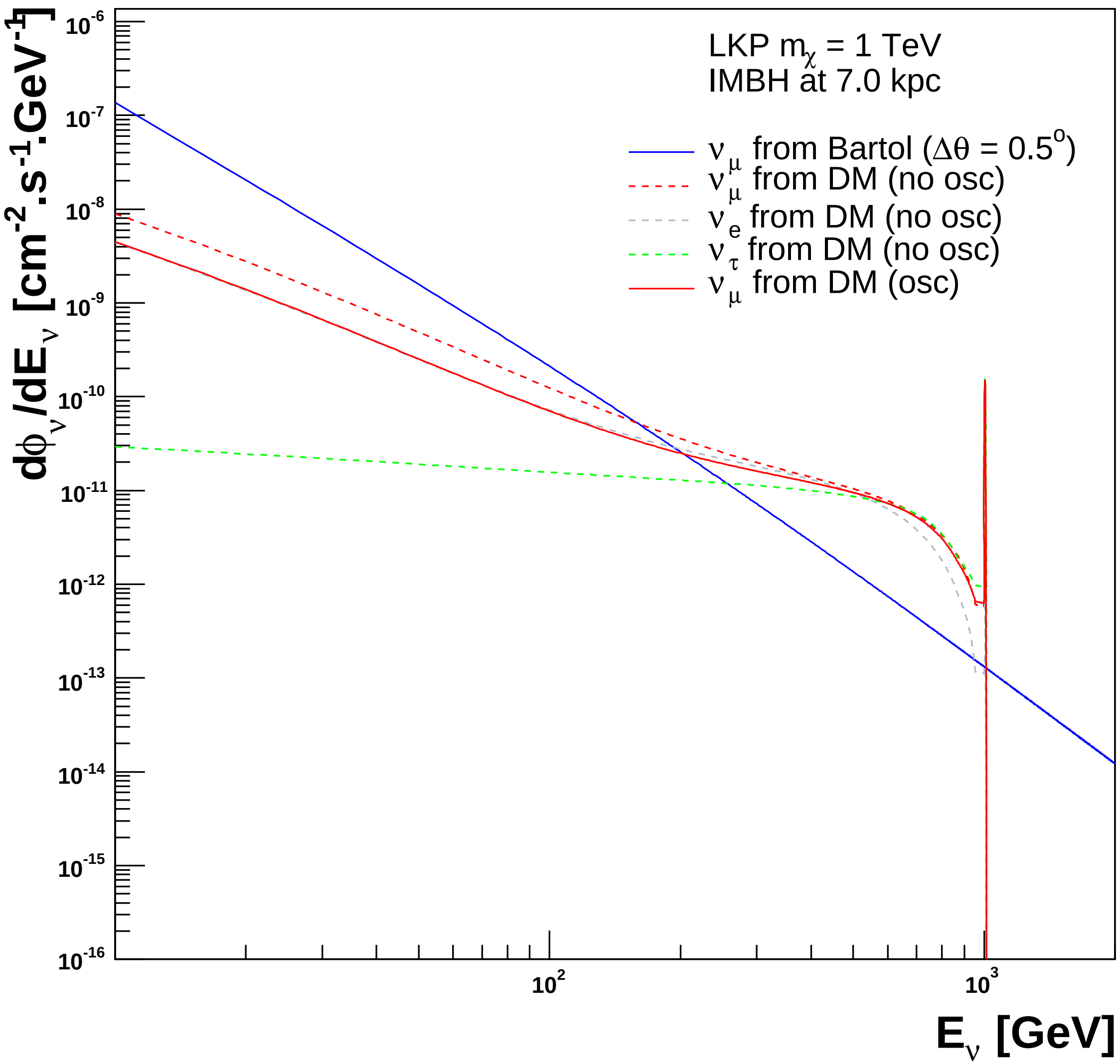
Expected flux for muon neutrinos

Neutrino angular resolution of 1°



Expected flux for muon neutrinos

Neutrino angular resolution of 0.5°



Reachable by ANTARES ?

Need to compute signal-to-background-fluctuation ratio. In the Poissonian background limit (On-Off strategy), the signifi cance level is:

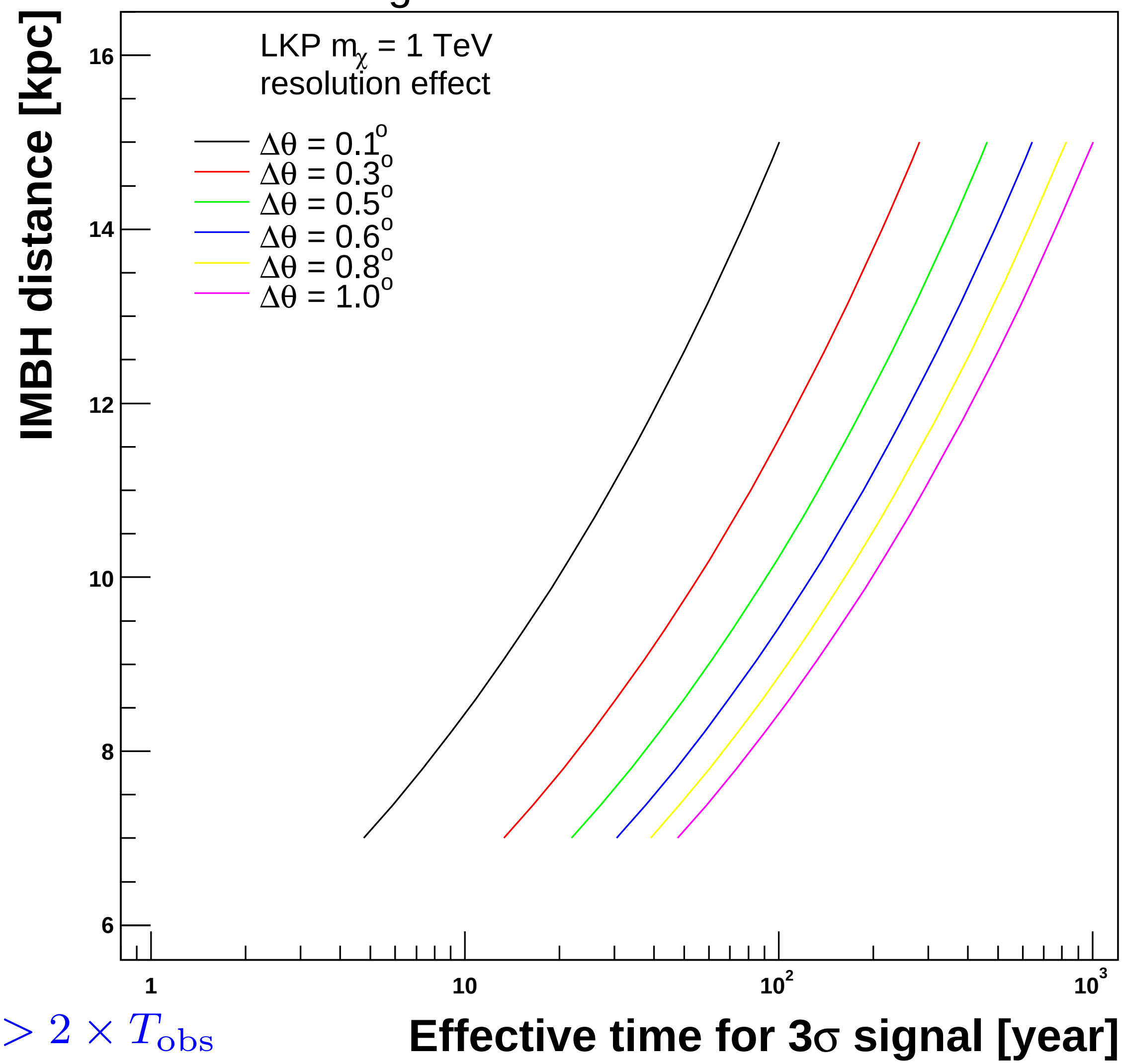
$$N_\sigma \simeq \sqrt{T_{\rm obs}} \frac{\int dE \int d\Omega \mathcal{A}(E,\theta) \times \frac{d\phi_{dm}(E,\theta)}{dE}}{\left(2 \int dE \int d\Omega \mathcal{A}(E,\theta) \times \frac{d\phi_{bg}(E,\theta,\phi)}{dE d\Omega}\right)^{1/2}} \quad \text{(-23)}$$

where $T_{\rm obs}$ is the effective time of observation (weighted and averaged over θ).
Crude assumptions ... very crude ... too much ???:

- Take an IMBH with $\delta = -42.5^{\rm o}$
- Take $\theta = 180^{\rm o}$
- Take $\Delta\theta$ constant over the whole energy range ...
- Low-energy-optimized Effective area
- Bartol-flux for background

Reachable by ANTARES (3σ) ?

Neutrino angular resolution from 0.5^o to 2^o



Actual time $> 2 \times T_{\rm obs}$

Global summary, conclusions and perspectives

- Annihilating dark matter is fairly well motivated
- Gamma-rays:
  - Gamma-rays offer a good potential for hints / constraints
  - Dwarf spheroidals with new generation IACTs !
  - Large fov survey for clumps
- Neutrinos
  - Unique signature from the Sun
  - Lack of other sources
  - Challenging
- **Complementarity !** (with cosmology, direct detection and colliders)